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SUMMARY

The WEST-1 wind turbine simulator is an implementation of mathematical models for an aeroelastic horizontal-axis wind turbine rotor using current hybrid electronics technology. High-speed digital and analog circuitry enable the computation of complex dynamic characteristics and performance of a wind turbine in real time. To test the ability of WEST-1 to predict blade fatigue load distribution, actual wind signals were fed into the simulator and the response data were recorded and processed in the same manner as actual wind turbine data. The WEST-1 simulator was operated in a stable, unattended mode for six hours. The probability distribution of the cyclic flatwise bending moment for the blade was comparable to that for an actual wind turbine in winds with low turbulence. The input from a stationary anemometer was found to be inadequate for use in the prediction of fatigue load distribution for blade design purposes and modifications are necessary.

INTRODUCTION

As part of the federal wind energy program, funded by the Department of Energy, various analytical tools have been developed for use in the design of horizontal-axis wind turbines. One of these developments is a wind turbine simulator called WEST-1, an acronym for Wind Energy System Time Domain-Unit 1 (ref. 1). The WEST-1 simulator is a hard-wired hybrid computer specifically designed to solve, in real time, the complex linear and nonlinear differential equations for the dynamic response of a wind turbine rotor. This real-time response permits an analyst to examine the dynamic behavior of a wind turbine design with steady state and transient wind conditions for extended periods of time.

The objective of this study is to evaluate the capability of the WEST-1 simulator in the prediction of blade fatigue load distribution when measured wind data are used for input. The approach used was to (1) model the DOE/NASA Mod-0 rotor on the simulator; (2) use recorded wind speed data from three anemometers as input to the simulator; (3) record, over a six hour period, eleven channels of simulator data such as rotor torque and power, blade bending moments, wind speed, and wind shear; (4) statistically process the output data particularly to determine the probability distribution of the cyclic flatwise bending moments at the blade root during the six hour period; and (5) compare the blade cyclic flatwise moment probability distribution from the simulator with that measured on a comparable wind turbine rotor under field test conditions.

This paper includes brief descriptions of the WEST-1 simulator and test setup, results from the simulator, and a comparison of blade load distribution obtained from the simulator and that obtained from a field-tested wind turbine.

DESCRIPTION OF WEST-1

The WEST-1 simulator models an aeroelastic horizontal-axis wind turbine rotor using current hybrid electronic technology (ref. 1). The mathematical models are implemented with a variety of analog, digital, and hybrid computational devices.

Hardware

The components of the WEST-1 simulator are housed in a printed circuit (PC) card cage enclosure shown in figure 1. The enclosure is 50 cm (20 in.) high, 52 cm (21 in.) wide, and 55 cm (22 in.) deep. It holds two card cage trays and one power supply tray. The top tray contains circuits which model wind speed, wind shear, tower wake and wind retardation. The middle tray contains all the circuits for the complex aeroelastic rotor model. The bottom tray contains the power supply and a test instrument for checking and calibrating the various types of PC cards.

Each PC card contains a number of electronic devices which perform a specific mathematical function. Analog devices include multipliers, summers, integrators, and potentiometers. Digital devices include logic inverters, NOR gates, J-K flip-flops, and one shots. Hybird devices include switches, multiplexors, sample-holds, comparators, and mode-controllable integrators.

WEST-1 contains one hundred and thirty-two (132) PC cards and uses over sixteen hundred devices. The PC cards are plugged into a card cage assembly called a "pin plane". One side of the pin plane receives the PC card edge connectors and connects each card circuit to a pin on the opposite side. The pins are wired to each other with a process called "wire-wrapping" to form the desired circuits.

Mathematical Models

As presently configured, WEST-1 has the capability to model a horizontal-axis wind turbine rotor with the following features: one to four blades; one aeroelastic degree-of-freedom per blade (hinged or cantilevered blade on a rigid hub); radial distributions of chord, twist, and mass; full or part-span pitch angle; constant rotor speed; linear wind shear; tower wake; and yaw angle. An auxiliary analog/digital unit can be used to model the dynamic response of other wind turbine components such as the power train, tower, and pitch control system.

The WEST-1 simulator uses a single degree-of-freedom modal representation for the aeroelastic properties of each rotor blade.The first out-of-plane or flatwise bending mode of the rotor blade is used. Aerodynamic and inertial forces are computed with blade element models. These forces are integrated radially to obtain generalized forcing functions and rotor shaft loads. The shaft loads from each blade are summed to produce total rotor shaft loads.

The air motion models implemented in the WEST-1 simulator include translational and rotational components of the wind with respect to the rotor, tower wake, and retardation of the wind by the rotor. A linear wind shear is modeled by the lateral rotational component of the wind. The tower wake is modeled by an adjustable step change in wind speed over an adjustable sector of the rotor disk. The Glauert momentum model is used to determine the wind retardation.

DESCRIPTION OF TEST SETUP

The WEST-1 simulator was set up for testing in the Mod-0 Wind Turbine Test Facility at the NASA Plum Brook Station in Sandusky, Ohio. Equipment, in place at this site, was used to provide wind input, blade pitch angle control, and record the output data.

Rotor Configuration

The WEST-1 simulator was programmed, by adjustment of approximately three hundred potentiometers, to model the DOE/NASA Mod-0 wind turbine rotor with aluminum blades (ref. 2). The basic characteristics of this rotor are:

(1) Two blades with a rotor diameter of 38 m
(2) Blade cone angle of 7°
(3) NACA 230XX series airfoil
(4) Blade chord distribution of 0.46 to 1.37 m (tip-to-hub)
(5) Blade twist angle distribution of -2° to 32°
(6) Blade thickness-to-chord ratio distribution of 0.12 to 0.44
(7) Blade natural frequency of 1.82 Hz for the first flatwise bending mode
(8) Rotor speed of 40 rpm
(9) Rated generator power output of 100 kW at wind speed of 8 m/s

WEST-1 Input Signals

The wind speed and wind shear input signals were taken from anemometer data at the site which had been previously recorded on analog tape. These recorded data provided over six hours of continuous time-varying wind input. Signals from three separate anemometers were used. The overall wind speed input was taken from the signal of an anemometer located at the elevation of the Mod-0 wind turbine hub. The difference in the signals from the other two anemometers located at elevations of 27 and 59 m provided the linear wind shear input.

The blade pitch angle input was controlled by a microprocessor external to the WEST-1. The microprocessor was programmed to monitor the power output signal and change the pitch angle input signal as needed to maintain rated power output in high wind conditions. The blade pitch angle was held constant near zero degrees in low wind conditions.

Other input parameters were set by controls on the front of the simulator. The rotor shaft speed was set at a constant 40 rpm. The tower wake was set to reduce the wind speed by 35 percent over a 24° sector based on wind tunnel tests of the tower model. The yaw angle was set at 0°.

WEST-1 Output Data Processing

The data from the simulation were recorded and processed in the same manner as those from actual wind turbine tests (ref. 3). Both input and output signals were digitized, screened for maximum and minimum values in each rotor revolution, and then recorded on magnetic tape. Recorded input data included wind speed, wind shear rotor shaft speed, yaw angle, and blade pitch angle. Recorded output data included rotor power, rotor shaft torque, blade root flatwise and chordwise bending moments, and blade tip deflections.

Subsequent processing produced midpoint and cyclic parameters of the recorded data according to the following equations:

$$\text{midpoint} = (\text{maximum} + \text{minimum})/2$$
$$\text{cyclic} = (\text{maximum} - \text{minimum})/2$$

The final processing yields a microfiche record containing the time history and two statistical summaries of each parameter. The time history plots contain the time history of thirty-second averages. One statistical summary is a distribution of the parameter partitioned into subsets of wind speed. The other summary is a cumulative probability distribution of the parameter.

RESULTS AND DISCUSSION

A continuous unattended 6-hour run of the WEST-1 simulator was made with pre-recorded anemometer signals used for wind input and with a microprocessor used for blade pitch angle control. The simulator operated in an automatic and stable mode throughout the entire period. Data were recorded and processed for analysis and comparison with actual wind turbine results.

Wind Input Time Histories

The time histories for the midpoint and cyclic values of the wind speed input to the WEST-1 simulator are shown in figure 2. The midpoint values varied continuously and ranged from 5 to 15 m/s. The cyclic values were relatively constant at a low level of about 0.2 m/s. The time histories for the wind shear input in figure 3 show very similar characteristics. The midpoint wind shear values varied frequently between zero and 4 m/s while the cyclic values were fairly constant around 0.2 m/s.

The variability of the midpoint wind speed values is characteristic of a moderately turbulent wind. The low cyclic values are due to normal signal noise and are indicative of a lack of substantial change within one rotor revolution at a stationary anemometer.

Blade Bending Moment Output

The blade flatwise bending moment output was selected to indicate the capability of WEST-1 in the prediction of blade fatigue loads. It is representative of the primary structural response of a horizontal axis wind turbine to variable wind conditions. The aeroelastic response of the blade

first flatwise bending mode is modeled in WEST-1. The cumulative probability distribution of the flatwise bending moments is of particular importance in the determination of blade fatigue loads.

Time histories for midpoint and cyclic values of blade flatwise bending moments from the WEST-1 run are shown in figure 4. Both curves reflect the variability of the wind input. The partioned distributions of these bending moment values with wind speed are given in figure 5. The pair of symbols on the vertical bars indicate the confidence interval (at the 0.95 level) for the differences in the median values for adjacent wind speed subsets. The horizontal tabs indicate the 16th and 84th percentile values.

In figure 5, the midpoint values show a peak near the rated wind speed of 8 m/s. This reflects the reduction of thrust loads in lower wind speeds at a fixed blade pitch angle and in higher winds speeds where the pitch control acts to limit the power output. This confirms that the blade pitch angle control was functioning properly.

The cyclic values in figure 5 increase with wind speed and are not influenced by the pitch control. This is reasonable because these cyclic values are primarily due to the wind shear and tower wake input, and the tower wake effect increases with wind speed.

The cumulative probability distributions for the midpoint and cyclic values of the blade flatwise bending moments from the WEST-1 run are given in figure 6. The midpoint values range from -77 000 N-m (-57 000 lb-ft) at the 0.01 percentile to 24 000 N-m (18 000 lb-ft) at the 99.99 percentile. The cyclic values range from 25 000 N-m (19 000 lb-ft) to 78 000 N-m (58 000 lb-ft).

Comparison of Blade Load Distributions

The wind turbine test data, used here for comparison with the WEST-1 simulator results, were measured on the DOE/NASA Mod-OA wind turbine at Clayton, New Mexico. An extensive set of data was recorded and processed and has been reported in reference 4. Although rated at 200 kW, the Mod-OA rotor is essentially the same as the Mod-0 rotcr configuration modeled in the WEST-1 simulator. As noted in the discussion of figure 5, this difference in power control does not signficantly affect blade flatwise cyclic loads.

A normalized plot of WEST-1 data and two sets of Mod-OA test data are presented in figure 7. The probability distributions for the blade cyclic flatwise bending moments of these sets are normalized with respect to their median (50th percentile) values. This normalizing removes differences due to mean wind speed, wind shear, pitch angle, and radial location, permitting direct comparison of the distribution slopes. The slopes can be used to calculate the log standard deviations for the various probability distributions.

The WEST-1 data set, shown in figure 7, is the normalized version of that presented in figure 6. The median wind speed was 10.0 m/s for the six-hour test run. The turbulence level was moderate.

The first Mod-OA data set in figure 7 is a comprehensive set compiled from 43 hours of test data (ref. 4). It includes data from tests covering the full range of wind speeds and turbulence levels. The median wind speed was 8.0 m/s for this data set. All levels of turbulence (low, moderate, and high) were encountered in these tests.

The second Mod-OA data set in figure 7 is a subset of the first. These data were obtained in a six-hour test run during which the wind turbulence level was low. The median wind speed was 7.4 m/s.

Straight-line curve fits through the data in figure 7 indicate log-normal distributions for the blade cyclic flatwise bending moments. The slope of the WEST-1 curve fit indicates a log standard deviation of 0.077. The comprehensive Mod-OA dataset has a significantly higher log standard deviation of 0.201. The Mod-OA subset with low-turbulence-level wind conditions has a log standard deviation of 0.073 comparable to that of the WEST-1.

The blade fatigue load distribution produced by the WEST-1 simulator is unconservative with regard to both Mod-OA data sets. The WEST-1 distribution is comparable to the six-hour Mod-OA distribution despite the lower wind speed and low turbulence level of the Mod-OA run. The blade load distribution of the comprehensive Mod-OA data set is substantially wider than that of the WEST-1 because of the wide range of wind speed and turbulence levels. However, it is this wider range of loads which the simulator must predict in order to become a useful design tool.

Apparently, based on the wind input and blade load response, the wind input derived from three stationary anemometers does not adequately model the character of the wind across the rotor disk. The low cyclic values of the wind input from a moderately turbulent wind produce cyclic blade loads comparable only to actual loads in low turbulence conditions. A wind characteristics study has shown that turbulence encountered by a point on a rotating blade is quite different than turbulence measured by a stationary anemometer (ref. 5). In that study, the spectral analysis of rotationally sampled wind data indicates significant amounts of energy in turbulence fluctuations at multiples of the rotational speed. These characteristics are not found in stationary anemometer data and are evidently needed in the wind input for the simulation of blade response to turbulent wind conditions. Thus modifications to the wind input are necessary to produce a blade fatigue load distribution useful for design purposes.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made from the results of the WEST-1 simulator run and the comparison with actual wind turbine data:

(1) The WEST-1 wind turbine simulator can operate in a stable unattended mode continuously for extended periods of time with time-varying wind input and microprocessor blade pitch angle control.

(2) The WEST-1 simulator with stationary anemometer wind speed input produces a blade fatigue load spectrum similar to wind turbine test data for low wind turbulence conditions.

(3) The wind signals from stationary anemometers are not adequate for input to the WEST-1 in producing blade fatigue load distribution for use in blade design.

It is recommended that further testing of the WEST-1 simulator be made with modifications to the wind speed input which would expand the range and increase the variations within each rotor revolution.

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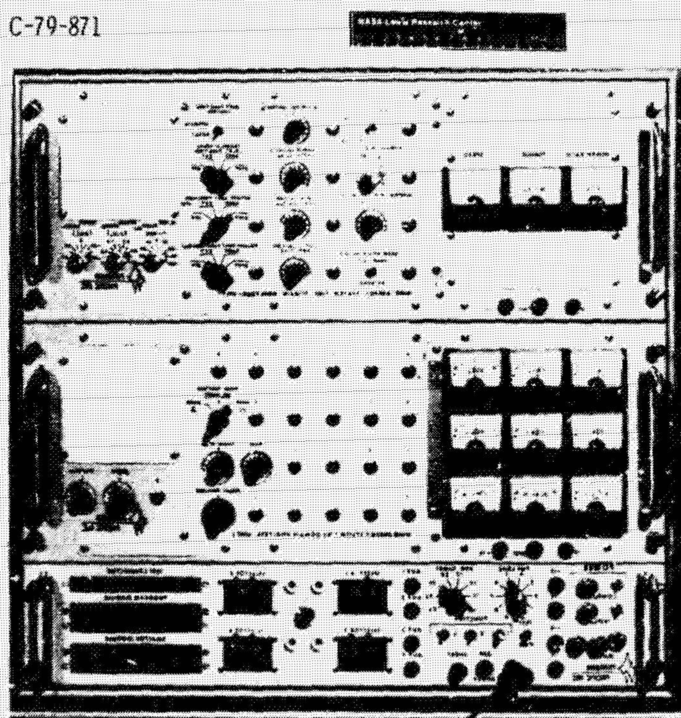

Figure 1. - Front panel of WEST-1 wind turbine simulator.

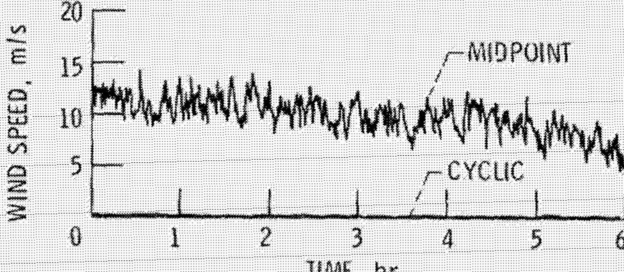

Figure 2. - Wind speed input to WEST-1 simulator from stationary anemometer.

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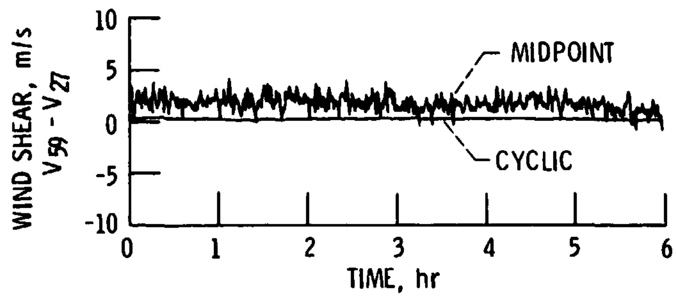

Figure 3. - Wind shear input to WEST-1 simulator from difference of anemometer signals at elevations of 59 and 27 meters.

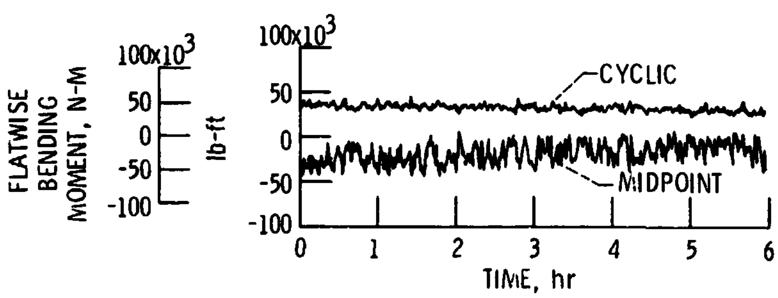

Figure 4. - Time history of blade flatwise bending moments from WEST-1 simulator.

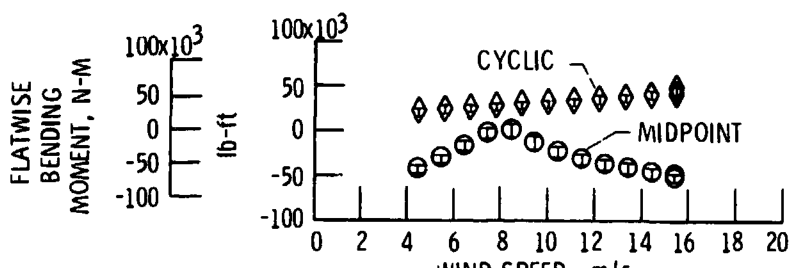

Figure 5. - Partitioned distribution of blade flatwise bending moments with wind speed from WEST-1 simulator.

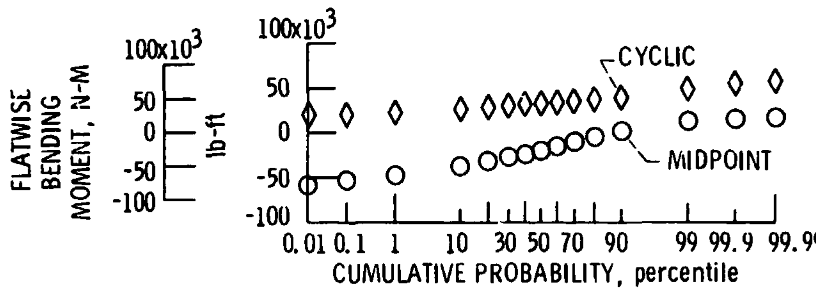

Figure 6. - Cumulative probability distribution of blade flatwise bending moments from WEST-1 simulator.

TEST CONDITIONS

	SOURCE	MEDIAN WIND SPEED, m/s	TEST PERIOD, hr	TURBULENCE LEVEL	LOG STANDARD DEVIATION
○	WEST-1	10.0	6	MODERATE	0.077
□	MOD-OA	8.0	43	ALL	.201
◇	MOD-OA	7.4	6	LOW	.073

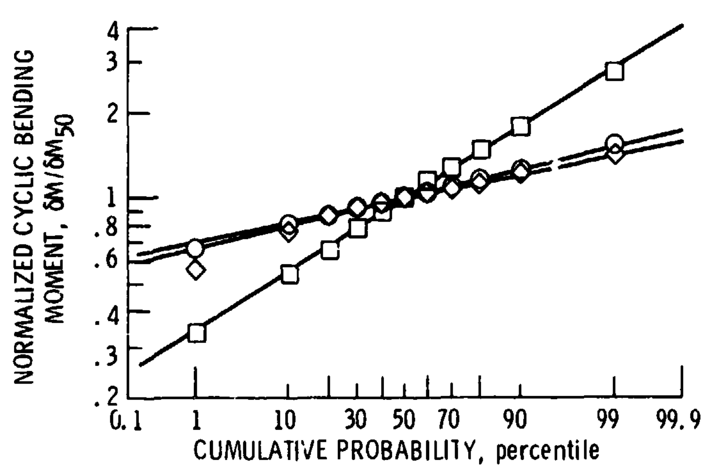

Figure 7. - Normalized blade cyclic flatwise bending moment probability distribution for WEST-1 simulator and comparable Mod-OA wind turbine test data.